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TITLE: OBSERVATION OF ν_e-e ELASTIC SCATTERING

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MASTER

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ABSTRACT

We present results to date from an experiment in progress by an Irvine, Los Alamos, and Maryland collaboration at the Los Alamos Meson Physics Facility (LAMPF) beam stop. We have observed a signal consistent with ν_e-e elastic scattering in a 15-metric-ton detector composed of modules of flash chambers and scintillation counters. A preliminary cross section for this process is compared to that expected from the GWS model that includes the interference between charged and neutral currents. We also set limits on the probability for exotic muon decay $\mu^+ \to e^+ \nu_\mu \bar{\nu}_e$ and on the neutrino oscillation mode $\bar{\nu}_\mu \to \bar{\nu}_e$ from normal muon decay $\mu^+ \to e^+ \bar{\nu}_\mu \nu_e$.

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INTRODUCTION

Purely leptonic processes, such as ν-e elastic scattering, provide critical tests of the validity of the electroweak theory of Glashow, Weinberg, and Salam[1] (GWS). There are several important checks on our current understanding of the electroweak interaction that would be provided by an accurate measurement of ν_e-e scattering. This process is mediated by both charged and neutral currents. A measurement of the total cross section for ν_e-e at the ≈25% level of precision would be sensitive enough to observe the interference between the charged and neutral currents and, if present, to determine the sign of this interference (i. e. constructive or destructive). This is an important check on the standard model of the electroweak interaction. We also note that observation of the interference would demonstrate that the outgoing neutrino from the neutral current is identical to the outgoing neutrino from the charged current.[2]

In addition, important checks on the validity of the nature of lepton-conservation laws and possible mixing of neutrinos can be made. Namely, in a beam-dump experiment at medium-energy facilities, an equal number of ν_μ, $\bar{\nu}_\mu$, and ν_e are produced by the $\pi^+ \to \mu^+ \nu_\mu$, $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$ decay sequence. The production of $\bar{\nu}_e$, which can be made normally through the analogous π^- decay sequence, is highly suppressed (10^{-3} or more) due to stopped-pion interactions in the beam stop. Thus observation of $\bar{\nu}_e$ interactions at a rate higher than expected would imply an anomalous mechanism exists for producing $\bar{\nu}_e$. Two possible mechanisms would be the exotic muon decay $\mu^+ \to e^+ \nu_\mu \bar{\nu}_e$ or the neutrino oscillation mode $\bar{\nu}_\mu \to \bar{\nu}_e$ where the $\bar{\nu}_\mu$ comes from normal muon decay $\mu^+ \to e^+ \bar{\nu}_\mu \nu_e$. Exotic muon decay is not allowed by the additive lepton number conservation law, but is allowed with a multiplicative law. Normal muon decay is allowed by either an additive or multiplicative law. Neutrino oscillations require that there exists a non-zero mass eigenstate in the neutrino system and that there exists a coupling that mixes neutrino types.

We present our results to date from an Irvine-Los Alamos-Maryland collaborative experiment conducted at the LAMPF beam stop in which we have observed events consistent with ν_e-e elastic scattering. A preliminary cross section for this interaction is compared to theory. We have searched for and not found events consistent with an incident $\bar{\nu}_e$. This allows us to set limits on neutrino oscillations of the type $\bar{\nu}_\mu \to \bar{\nu}_e$ and on the multiplicative lepton number conservation scheme.

EXPERIMENTAL SETUP

The neutrino detector consists of 40 modules of scintillation counters and flash chambers. Each module is composed of four scintillator slabs, each 76 cm wide, 305 cm long, and 2.5 cm thick arranged into a single layer of 305 cm on each side. These provide energy and energy-loss (dE/dX) information that is required for the logic trigger. The trigger is provided by a coincidence system (ADL) which requires that at least three adjacent layers of scintillators register a pulse height of more than ≈0.9 MeV but less than ≈16 MeV.[3] The flash chambers are arranged into 10 layers of alternating coordinate readout (five horizontal and five vertical planes) in order to provide tracking information. They are pulsed after a coincidence is registered by the ADL's that is not accompanied by activity in an anti-coincidence shield either coincident with the trigger or up to 20 μs before the trigger. This delay is necessary to eliminate cosmic muons that enter the detector, stop, and subsequently decay. Due to the 6-9% duty factor of the LAMPF machine, an extensive anti-coincidence shield composed of four layers of extruded-aluminum proportional tubes located between lead, iron, and concrete shielding surrounds the central detector on all sides. The chambers are operated in a two-out-of-four coincidence requirement and achieve a residual inefficiency for charged particles of $\approx 2*10^{-5}$ with a dead time of less than 15% to the experiment. The energy-resolution from the scintillators is ≈±10%, and the angular resolution from the flash chambers is ≈±7°. The center of the detector is located about 9 m from the beam stop.

Data were accumulated during the LAMPF beam-spill time and also when the beam was off. Typically, the beam microstructure was 750 μs beam-on followed by 7.55 ms beam-off. Beam-off data were taken approximately four times as long as beam-on data between the beam-on spills so that the uncertainty of the experiment was not dominated by the beam-off subtraction. The time-averaged proton current was ≈600 μA ($3.7*10^{15}$ protons/s) with 760-MeV kinetic energy incident on the beam-stop for this data sample.

The detector was pulsed approximately once per 10 live-seconds by events which passed the trigger requirements. Data were recorded on magnetic tape that represented the flash-chamber data, the pulse height and times of the coincident scintillator data, the pulse-height and times of scintillators that had >1 MeV of energy deposited during the 32 μs period before the event, the pulse height and times of the scintillators that had >2 MeV of energy deposited during the 68 ms

after the event, and the history of the anticounters during the 32 μs preceeding the event. In addition, calibration events of muons that entered the detector and subsequently decayed and muons that passed entirely through the detector were taken approximately every 10 minutes. A total of about 3000 events was taken each day. Data were accumulated for a total of 0.97 Ampere-hours of protons ($2.2*10^{22}$) on the beam stop.

DATA REDUCTION

The first stages of data reduction removed those events which were induced by cosmic events that remained after the hardware trigger. A fiducial volume cut was imposed that removed those events that passed through the first or last layers of the detector or those that passed within the 5 cm near the side, top, or bottom of the detector. Events that had no reconstructable track in any view of the flash-chambers were also removed. In addition, high energy events (energy deposited in the scintillator of >60 MeV, corresponding to about 100 MeV total) were removed. These cuts, designated as Level 2 cuts, reduced the number of events by about a factor of 10.

Most of the remaining events were removed by tightening the dE/dX requirement. This removed many proton-recoils and electron-positron pairs that came from neutron-induced events (both beam-associated and cosmic). Events that recorded energy in more than one contiguous group of scintillators were also removed. These cuts reduced the data sample by about another factor of 10. In order to decrease the sensitivity of the results to residual beam-associated neutron induced events, cuts were also imposed to require that at least four adjacent layers of scintillation counters had pulse-height patterns consistent with a single electron with the total recorded energy greater than 35 MeV (total energy greater than 55 MeV) .

MONTE CARLO SIMULATION AND DETECTION EFFICIENCY

A Monte Carlo simulation of the detector was developed so that the response of the detector to electrons could be understood. This included radiative energy loss and production of secondaries from photon conversion. The core was the EGS code.[4] In addition, several aspects of the reconstruction efficiency and resolutions were understood by passing calibration events through the analysis

code and by generating calibration events in the simulation. Fig. 1 shows the observed energy deposited in the scintillators for stopped muon decays from cosmic muons. The predicted spectrum generated by the simulation and then filtered through the same cuts as required by the analysis code is also shown. The agreement provides confidence on the ability of the simulation to duplicate the absolute energy scale of the apparatus.

By examining the sensitivity of the experiment to possible uncertainties in the energy scale and to the analysis cuts, we are confident that we understand the absolute efficiency of the detector and of the analysis code to ±8%.

RESULTS

The results we have obtained to date are shown in Fig. 2. This shows the angular distribution of events that have survived the trigger and analysis cuts. Fig. 2a shows both the beam-on and beam-off angular distribution normalized to equal live times after the Level 2 cuts. An excess of beam-on events is clearly seen. Fig 2b shows the beam-associated events that have passed all the analysis cuts. The peak with $\cos\theta > 0.96$ is kinematically consistent with $\nu_e e$ elastic scattering. A background of events that contribute to the signal at all angles is also evident. The contribution of beam-associated events from neutron-induced events had been studied during a series of measurements in which the shielding between the beam stop and the detector was varied. The results of this study indicated that the background from neutron events near 0° was <5% of the expected $\nu_e e$ rate. The peak near 0° contains 24.4±6.8 events; a subtraction of 4.0±3.0 events is applied for events that contribute at all angles. This leaves 20.4±7.4 events consistent with $\nu_e e$ scattering. To compare this number of events with theory, the GWS predictions for $\sin^2\theta_W = 0.22$ were generated in the simulation. This included the neutrino flux and uncertainty (±12%), the efficiency and uncertainty of the absolute trigger and energy deposition efficiency for forward going recoil electrons (±8%), and the reconstruction and cut efficiency (±10)%. The simulation predicts that 16.7±3.5 events would have been seen for the case of destructive interference. Likewise, we would have expected 45.8±3.6 events for constructive interference, and 31.3±5.9 events for no interference between the neutral and charged currents.

Thus, the preliminary results of this experiment to date show agreement with that expected from the GWS model with destructive interference and rule out

constructive interference at the 90% confidence level (c. l.). The uncertainties are presently too large to claim that the interference between the charged and neutral currents has been observed.

In order to extract a cross section for ν_e-e elastic scattering, the contribution of ν_μ and $\bar{\nu}_\mu$ induced events must be subtracted. Using the GWS model for the recoil electron distribution with current values for the cross sections for ν_μ-e and $\bar{\nu}_\mu$-e scattering and the flux of ν_μ and $\bar{\nu}_\mu$ from the beam stop, 0.7±0.2 event would be expected in this sample from ν_μ-e scattering and 3.4±1.2 events from $\bar{\nu}_\mu$-e scattering. This is not significantly different from the number of ν_μ and $\bar{\nu}_\mu$ events which would be subtracted by using GWS predictions. Thus the data are left with 16.3±7.5 events consistent with ν_e-e scattering. The total cross section for ν_e-e elastic scattering is $(10.6\pm4.8(\text{statistical})\pm1.9(\text{systematic}))*10^{-45}*E_\nu(\text{GeV})\text{cm}^2$.

In order to search for events that could have been induced by $\bar{\nu}_e$ reactions either from $\bar{\nu}_\mu\to\bar{\nu}_e$ oscillations or from exotic muon decay, the kinematic regions $\cos\theta > 0.96$ and recoil electron energy <35 MeV (observed energy <23 MeV) were eliminated. The angle was chosen to eliminate ν_e-e elastic candidates; the energy was chosen to be greater than that expected from the ν_e-$^{12}C \to e^-$-^{12}N (all stat.) reaction. The Monte Carlo code was used to simulate the $\bar{\nu}_e p\to e^+n$ reaction. If 100% of the μ^+ decayed to $e^+\nu_\mu\bar{\nu}_e$, then we would have expected 750±130 events to satisfy the trigger and analysis requirements. Since 5±8 events were observed, the result is that the ratio of exotic μ decay to normal μ decay is less than .023 at the 90% c. l.

For neutrino oscillations of the type $\bar{\nu}_\mu\to\bar{\nu}_e$, the expected number of $\bar{\nu}_e$ for an initially pure state of $\bar{\nu}_\mu$ is $N\sin^2(2\theta_{mix})\sin^2(1.27L(\Delta m)^2/E)$, where N is the initial number of $\bar{\nu}_\mu$, Δm is the mass difference between the two neutrino mass-eigenstates in eV with mixing parameter $\sin\theta_{mix}$, L is the distance from the beam stop to the detector in meters, and E is the energy of the neutrino in MeV. Integrating the acceptance over the allowed ranges of L and E, we find the asymptotic limits for neutrino oscillation at the 90% confidence level are $(\Delta m)^2<0.63\ \text{eV}^2$ (large $\sin^2(2\theta_{mix})$) and $\sin^2(2\theta_{mix})<.045$ (large $(\Delta m)^2$).

FUTURE PLANS

We are in the process of taking several more months of data this summer

(1984) with additional cosmic shielding that should reduce the beam-off to beam-on ratio for possible elastic scattering events to better than the 1 to 1 we currently have. We will also attempt to reduce the trigger thresholds so that we can increase the low-energy efficiency of the detector. After this summer, additional material will be placed between the beam-stop and the detector in order to reduce the beam-associated signal from neutron-induced events. In addition, a separate experiment will be conducted that will determine the neutrino flux per incident proton from the LAMPF beam stop. We expect that we will be able to increase the efficiency and consequently reduce the uncertainties of the analysis compared to the Monte Carlo simulation of the performance of the detector. These factors should allow the systematic uncertainties to be reduced to below ±10%. We also expect a substantial increase in the sample of events consistent with ν_e-e scattering.

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FIGURES

Fig. 1. Energy deposited in the scintillators for cosmic-ray muon decays. The Monte Carlo simulation is also shown. The gains of the counters were determined by minimum-ionizing particles passing through the entire detector.

Fig. 2a. Number of events that pass the Level 2 cuts for both beam-on and beam-off vs the cosine of the angle between the recoil particle and the direction of the neutrino source. The beam-off events have been normalized to an equal amount of live-time as the beam on events.

Fig. 2b. Excess of beam-on events after final cuts vs the cosine of the angle between the recoil particle direction and the direction of the neutrino source. Neutrino-electron scattering events are expected to concentrate near $0-0^{o}$ ($\cos\theta \approx 1.0$).

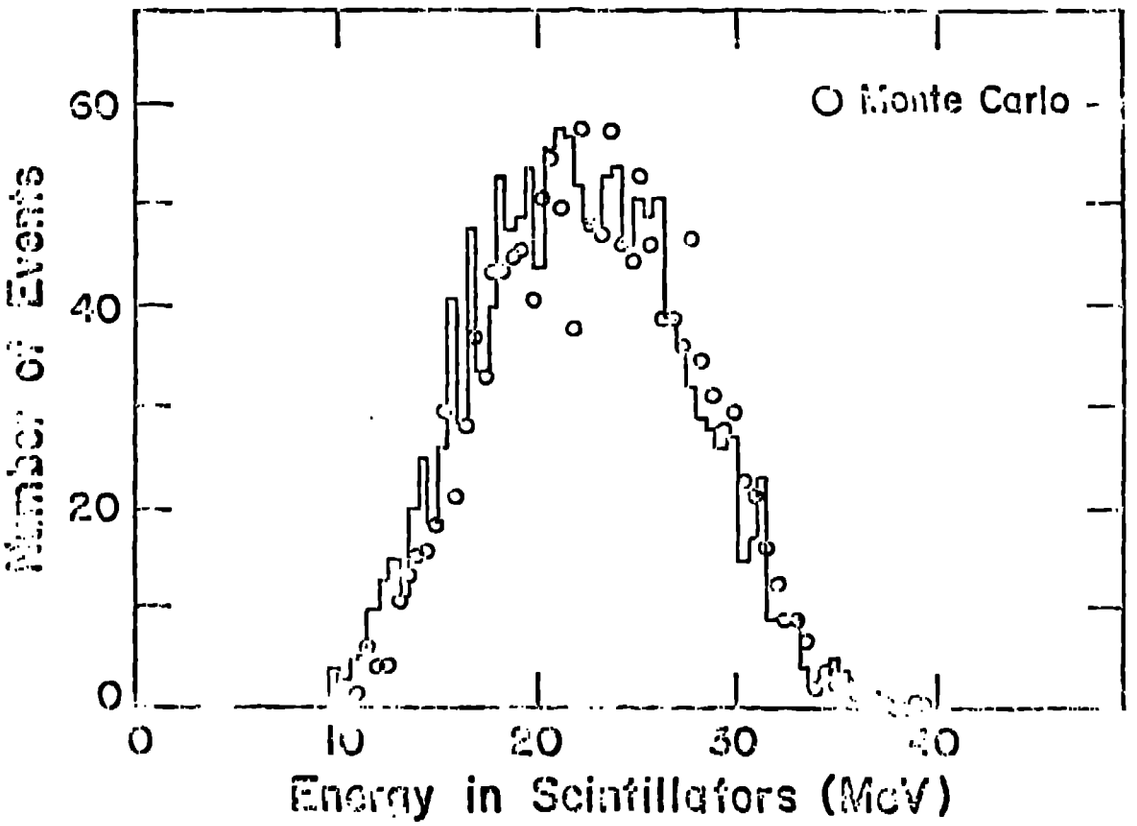
O Monte Carlo
Number of Events
60
40
20
0
0
10
20
30
40
Energy in Scintillators (MeV)

Fig. 1

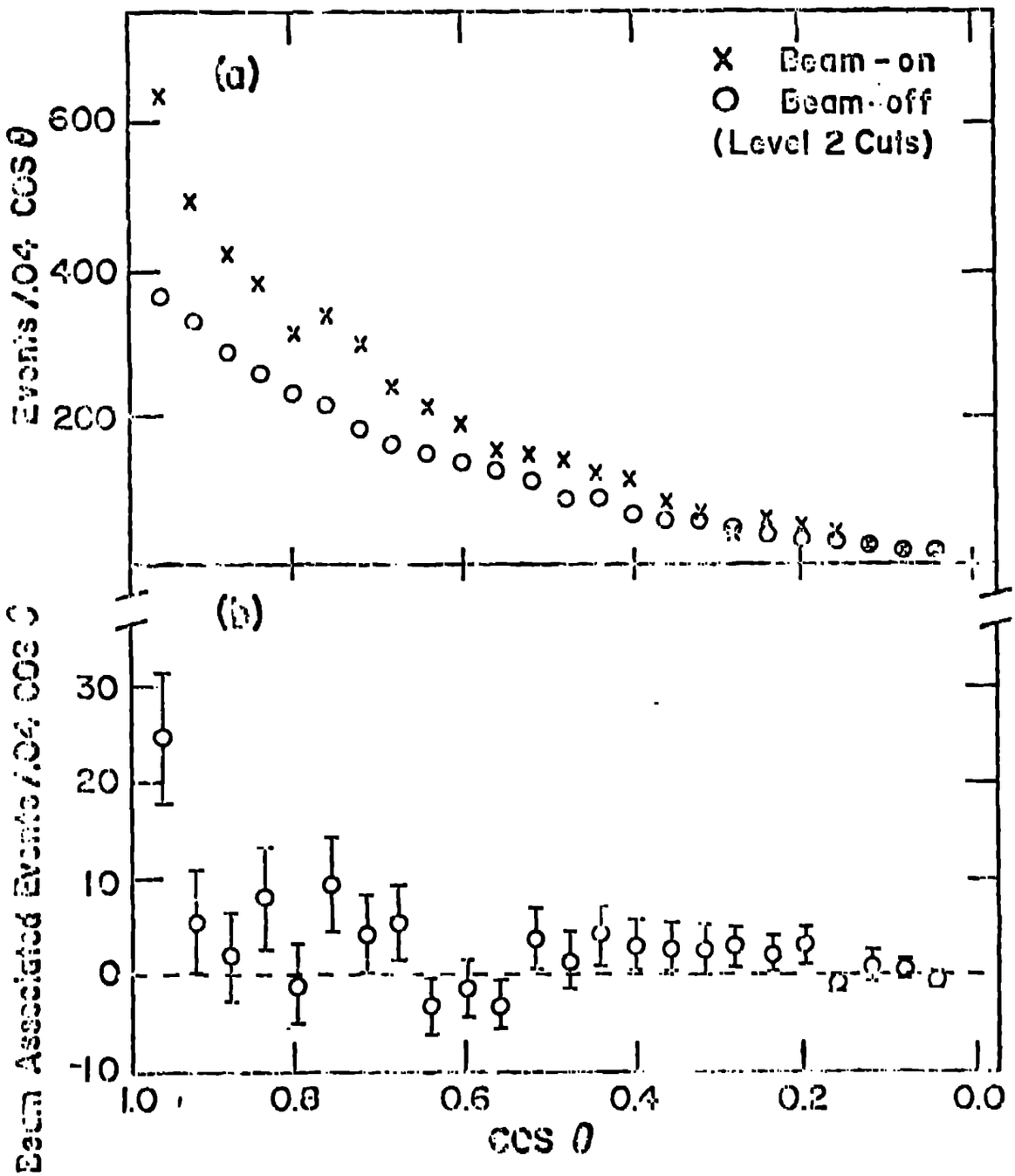
(a)
X Beam-on
O Beam-off
(Level 2 Cuts)
Events/.04 cos θ
600
400
200
(b)
Beam Associated Events/.04 cos θ
30
20
10
0
-10
1.0
0.8
0.6
0.4
0.2
0.0
cos θ

Fig. 2